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14. ABSTRACT
Since the first demonstration of negative refractive index using nested or edgecoupled split ring resonators and posts, various proposals have been made for improvement of the structures. Loss is an ongoing concern for these media at microwave frequencies and above. One alternate design uses broadside coupled split rings printed front to back on a substrate. This approach, which avoids bianisotropic effects of edge coupled rings, has been demonstrated successfully inside waveguide below cutoff . Our work here investigates the combination of similar broadside coupled rings (BCRs) with negative permittivity posts in a metamaterial prism, rather than the previous guided-wave medium. Free space measurement of negative refraction through a prism has become our standard for proof of negative index. Unlike rectangular wave guide, free space measurement also allows true transverse electromagnetic illumination. To observe the different effects of magnetic and electric coupling in the rings, two different orientations of the ring gap were used. One type has the gap aligned with the post and is symmetric about the electric field axis. The other has the gap turned 90 degrees from the post. The broadside coupled version of each orientation is measured and compared to a single ring version of the same dimensions and orientation for a total of four prisms.

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Free Space Measured Loss Comparison of Single and Double Ring Resonators for Negative Index Media

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Introduction

Since the first demonstration of negative refractive index using nested or edge-coupled split ring resonators and posts [1], various proposals have been made for improvement of the structures. Loss is an ongoing concern for these media at microwave frequencies and above. One alternate design uses broadside coupled split rings printed front to back on a substrate. This approach, which avoids bianisotropic effects of edge coupled rings, has been demonstrated successfully inside waveguide below cutoff [2,3]. Our work here investigates the combination of similar broadside coupled rings (BCRs) with negative permittivity posts in a metamaterial prism, rather than the previous guided-wave medium. Free space measurement of negative refraction through a prism has become our standard for proof of negative index. Unlike rectangular wave guide, free space measurement also allows true transverse electromagnetic illumination. To observe the different effects of magnetic and electric coupling in the rings, two different orientations of the ring gap were used. One type has the gap aligned with the post and is symmetric about the electric field axis. The other has the gap turned 90 degrees from the post. The broadside coupled version of each orientation is measured and compared to a single ring version of the same dimensions and orientation for a total of four prisms.

Design and Fabrication

The four unit cells used are shown in Fig. 1. The unit cell is 4.1 mm square. The post width is 0.76 mm. The ring outer radius is 1.70 mm, width is 0.25 mm and gap is 0.58 mm. The single ring designs were etched in 1 oz. copper on 0.25 mm thick Taconic TLY-5 substrate, which has dielectric constant 2.20 and dissipation factor 0.001 at 10 GHz. The double rings were formed by aligning two single ring boards with gaps opposed and gluing along the top and bottom edges only. Each unit cell was modeled in Ansoft HFSS using periodic boundary conditions. As usual for negative index media, the electric field is parallel to the length of the posts and the magnetic field is orthogonal to the plane of the rings. The simulation results are shown in Fig. 2.

To form prisms, the etched boards were spaced by 3.2 mm layers of Eccosorb PP2 foam, which are essentially transparent to microwaves. The flat, entrance face of the prisms was 20 cm by 25 cm. The minimum thickness was 5 unit cells (20.5

mm). The exit face of the prism was stepped to produce a 12 degree apex angle for the single ring design, and 11 degree apex for the double rings.

Measurements

The measurements were performed in free space using identical transmit and receive horns. The horns are 20 cm x 20 cm with a 3dB beam width of 14 degrees. The transmit horn was mounted 3.73 m from the prism. The prism was fitted into a 1.5 m x 1.5 m baffle. The receive horn was mounted on an arm 2.58 m from the prism and rotated about the exit face normal in one degree steps to measure the angle of refraction from 8-18 GHz. The HP 8530 receiver system was calibrated by measuring the signal through the open baffle with the horns aligned.

Analysis

As expected, the single ring with gap turned does not transmit well and the signal was at the noise floor of the system across the band. For the other three prisms, the magnitude and angle of the peak transmitted power were determined from the data for each frequency. The index of refraction n was then calculated using the Snell's law equation

$$n \sin(\alpha) = \sin(\theta)$$

where α is the prism angle, either 11 or 12 degrees, and θ is the measured angle of refraction from the normal in air. More detail of the technique appears in [4]. The plots in Fig. 3 show the measured refractive index and power versus frequency.

Consider the single ring cells first. As mentioned, the measured transmission through the prism of the single ring with gap turned from the post is negligible. In this unbalanced, bianisotropic orientation, the ring couples to both the electric and magnetic fields. In contrast, the single ring with gap along the post couples only to the magnetic field. Its simulation shows two widely separated resonances, one at 12 GHz and another at 20 GHz. The measurements yield a negative index passband beginning with a value of -1.6 at 13 GHz , crossing zero index at 15 GHz and continuing positive above that.

The BCRs are symmetric about the electric field for both gap orientations and both produce negative refraction. The simulation with gaps along the post produced two widely separated resonances at 9 GHz and 15 GHz. The measured data show two widely separated passbands. One is associated with negative index between 9 and 10.4 GHz. The other band above 13 GHz is positive. The only simulation to agree substantially with measurements is the double ring with gaps turned from the posts, where the rings couple to both electric and magnetic fields. The simulation shows two resonances at 9 and 12 GHz with a dip between. The actual measurements show a negative passband beginning at 9.2 GHz that crosses zero index at 10.5 GHz with a small dip in magnitude and continues with positive refraction out to 12.5 GHz.

The most significant result of these measurements is the comparison of maximum transmitted power in the negative passband. For the double rings with gap turned from the posts, the peak power occurs at 10.0 GHz with 31% of the open baffle power, and corresponding index of refraction n equal to -0.8. The double rings with gap along the post have a measured peak of 46% at 9.7GHz with index of -1. However, the single ring with gap along the post has a negative passband peak power of 70% at 14 GHz with index at -0.3. Despite the higher frequency of operation, the peak power is significantly higher for the single ring. Looking at the single ring data for an index near that of the double ring peaks, the transmitted power at 13.5 GHz with index of -0.9 is 37%, similar to the double ring peaks.

Conclusions

In free space, the split ring and post metamaterial of our design is very sensitive to the orientation of the single ring gap. A gap turned from the post (and the electric field) has no passband. The symmetric gap aligned with the post and the electric field produces a joined negative and positive passband. This difference in response further complicates the quest for isotropic media. The balanced BCR metamaterial is less sensitive, with both aligned and turned gaps producing negative passbands. However, the turned rings showed a joined positive passband while the aligned rings had a stop band between the negative and positive bands. The negative passband peak power for the BCRs was lower than the single ring, but occurred near an index of -1. This index is technologically interesting for low reflection applications such as radomes. The single ring peak power occurred nearer zero index, which is more interesting for antenna applications. The choice of resonator could be influenced by the desired application. Further work is being done to understand the loss mechanisms and the properties of bianisotropic structures compared to non-bianisotropic.

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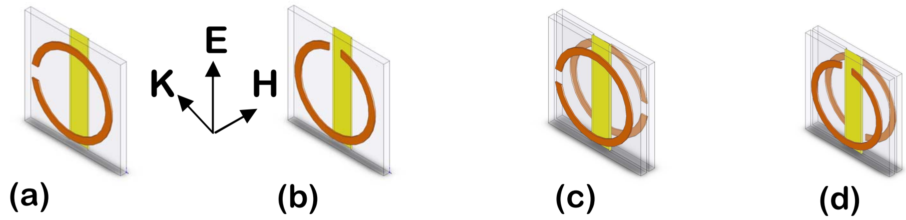

Fig. 1. Unit cells with incident vector. (a) single, gap turned (b) single, aligned (c) double, turned (d) double, aligned

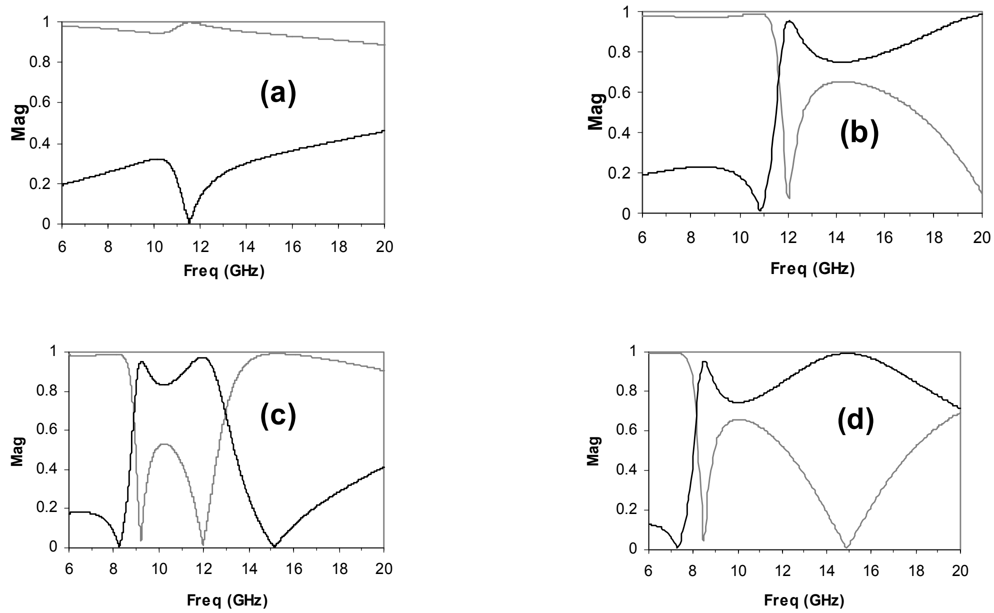

Fig. 2. Simulated S11 and S21 for a,b,c,d cells as in Fig. 1.

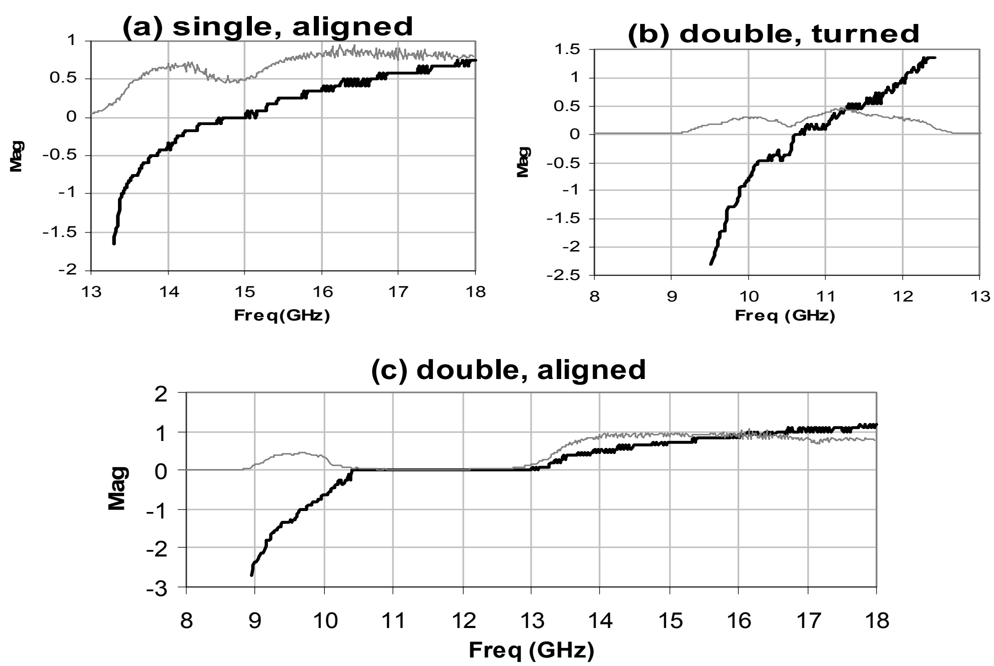

Fig. 3. Measured peak power and refractive index .